Fast Meets Cold: Ultrafast Coherent Control on a Single Ion

David Moehring*, Martin Madsen, Peter Maunz, Kelly Younge, Rudy Kohn, Jr., and Chris Monroe

FOCUS Center, University of Michigan

Department of Physics

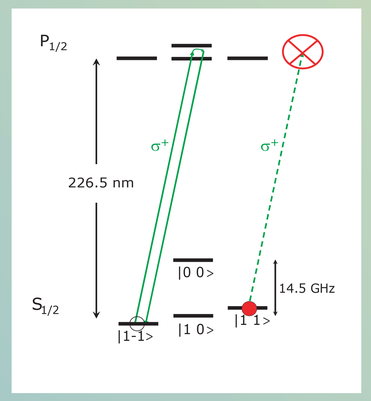
*email: dmoehrin@umich.edu

Continuous wave lasers have traditionally been used for atomic slowing, cooling, and internal state manipulation. The use of ultrafast laser pulses opens new possibilities for controlling both the internal and the external atomic degrees of freedom. We study this using a picosecond, modelocked laser tuned on resonance with atomic transitions in trapped cadmium ions. Here, we present a series of experiments, including observation of optical Rabi oscillations on a picosecond time scale, ultrafast coherent control of hyperfine qubit superpositions, precision measurement of excited state lifetimes, and a demonstration of broadband laser cooling.

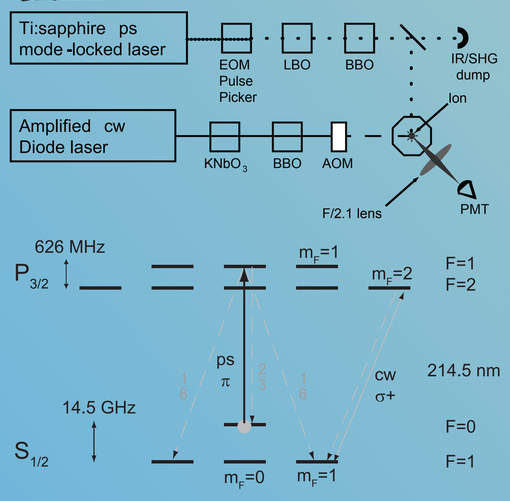
Fast Quantum Logic Gates

We consider a resonant excitation where the pulsed laser center frequency is tuned to the optical transition in the ion. By applying a series of spin-dependent kicks, a quantum phase gate can be realized on a pair of trapped ions. The kick amplitudes and times should satisfy the condition that the motional state of the ions is preserved at the end of the pulse sequence, while a non-zero phase is acquired. In the example shown to the right, the two qubit states are the Zeeman levels of $S_{1/2}$ F=1 hyperfine manifold of a $^{111}Cd^+$ ion. A σ^+-polarized pulse would couple the |1,-1> state to the excited $P_{1/2}$ state, while the |1, 1> state will not be affected. To avoid decoherence due to spontaneous emission from the P state, a pair of counterpropagating ps pulses should be applied, separated by much less than the excited state lifetime, which would return the ion to the ground state, resulting in a spin-dependent momentum kick of 2hk.

J.J. Garcia-Ripoll, P. Zoller, and J.I. Cirac, *PRL* **91**, 157901 (2003).

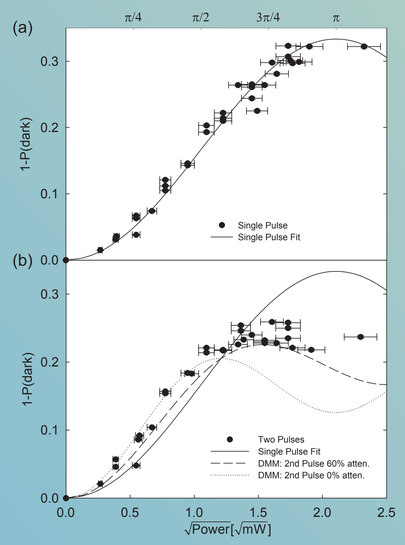


Ultrafast Optical Rabi Flopping

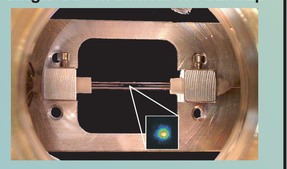


Left: Experimental apparatus and relevant energy levels used in the ultrafast coherent control experiments. The pulse picker allows delivery of identically one ps pulse to the ion.

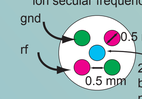
Right: (a) A single laser pulse excites the ion and after spontaneous emission, has a maximum brightness of 1/3. (b) After a short delay, second retro-reflected pulse is directed onto the ion. The theory curves shown are from a density matrix model (DMM).



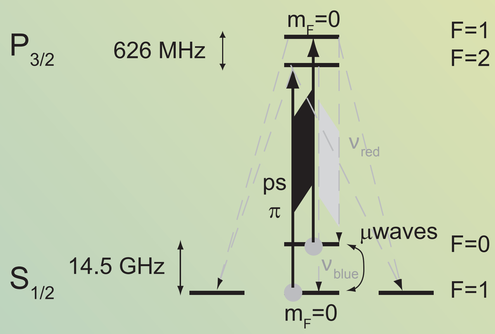
Single Cd^+ in a linear rf Paul trap



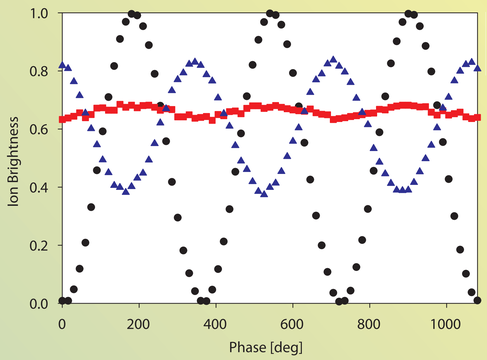
A single Cd ion trapped in a four rod linear rf Paul trap.
drive frequency: 35 MHz
ion secular frequency: ~1 MHz



Ultrafast Qubit Manipulations



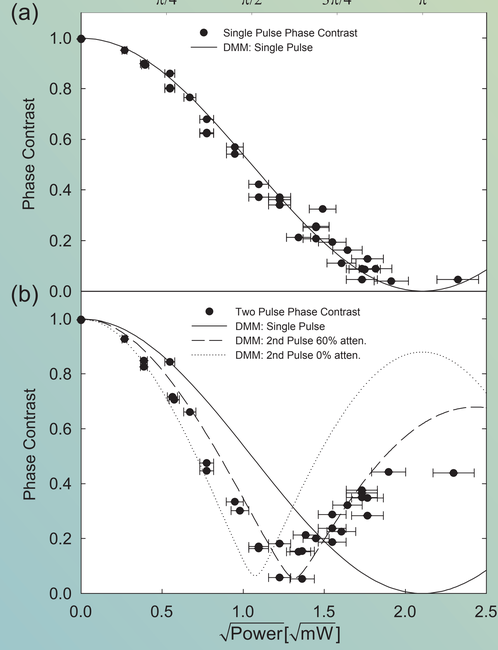
The ion starts in a superposition of two ground states. A single laser pulse excites both states to a superposition of excited hyperfine states. A second pulse then de-excites the superposition back down to the ground state



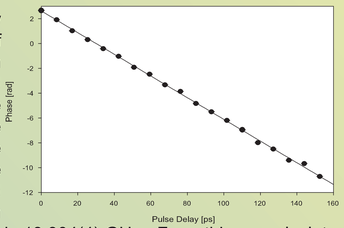
Ramsey fringes with no pulsed laser interaction (circles), only an excitation pulse (squares), and excitation followed shortly by de-excitation (triangles). The phase shift of 18.9*π of the Ramsey fringes following excitation and de-excitation compared to the Ramsey fringe without the laser pulses is due to the qubit frequency shift of 13.904 GHz during the 680 ps delay between the excitation and de-excitation pulses.

Ramsey Fringe Contrast

(a) A single laser pulse drives the ion to the excited state. Upon spontaneous emission, the Ramsey fringe coherence is lost. (b) When driven back down to the ground state via a second pulse, the coherence is regained. Numerical solutions to a density matrix model (DMM) are shown in both graphs.



The phase of the Ramsey fringes as a function of the time delay between the excitation and de-excitation pulses. The vertical error bars are found by a χ^2 fit to the Ramsey fringes. The slope of the line is found via the analytical solution to a linear fit problem and is 13.904(4) GHz. From this we calculate the $P_{3/2}$ hyperfine splitting to be 626(4) MHz.

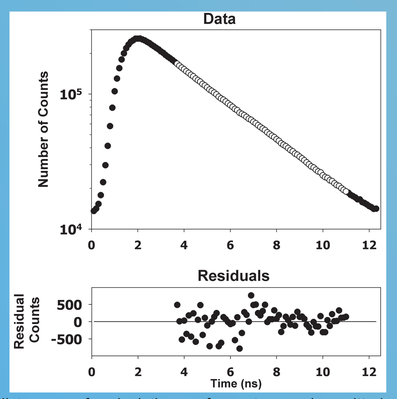


These experiments show the fundamental requirements for not only the Garcia-Ripoll, Zoller and Cirac ultrafast gates mentioned earlier, but also give evidence for entanglement between the atomic (hyperfine) qubit and the photonic (frequency) qubit. Additionally, because this method of ion-photon entanglement can be performed on initial hyperfine qubit superpositions, it can be further used for nonlocal quantum logic gates through a photonic coupling.

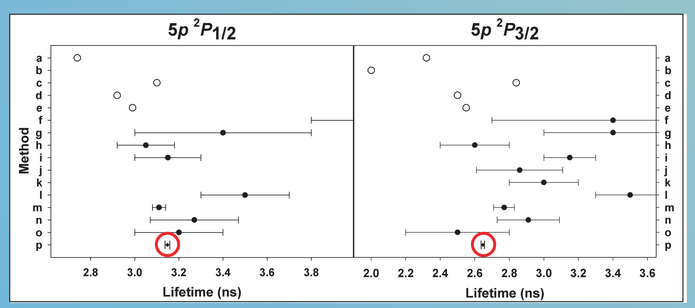
For more information on this latter part, see the poster by Peter Maunz, also presenting in this session.

Precision Lifetime Measurements

We perform precision measurements of the excited state lifetime of the 5p $^2P_{1/2}$ and the 5p $^2P_{3/2}$ levels of a single trapped Cd^+ ion. The ion is excited with picosecond laser pulses from the mode-locked laser and the distribution of arrival times of the subsequent spontaneously emitted photons is recorded. With this technique, we are able to eliminate prevalent systematic errors, such as: pulse pileup, radiation trapping, flight from view, subradiance or superradiance, and by using ultrafast laser pulses, eliminate potential effects from applied light during the measurement interval. These results are not only the most precise measurements to date for these levels, but with absolute uncertainties of order 10 ps, are among the most precisely measured excited state lifetimes in any atomic system. Additionally, this technique has the potential to achieve ~100 ppm precision.



Histogram of arrival times of spontaneously emitted photons as a function of time after the excitation pulse. The open circles show the data used to extract the excited state lifetimes, and the residuals show the goodness of our fit.



3.148 ± .005 ± .010 ns ± 0.35%

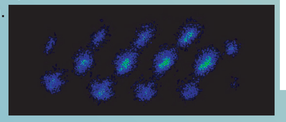
2.647 ± .002 ± .010 ns ± 0.38%

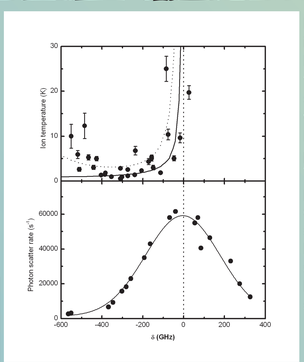
Moehring *et al.*, *PRA* **73,** 023413 (2006)

All published results of theoretical (open circles) and experimental (filled circles) lifetimes of these excited state levels. Our work is shown on the bottom (p) indicated by filled diamonds.

Broadband Cooling with Ultrafast Pulses

One common feature of nearly every laser cooling method today is the use of narrow-band, continuous-wave (cw) lasers, which efficiently cool atoms in a narrow velocity range. In order to increase the velocity capture range, some "broadband" cooling methods have been developed by modulating a cw beam. Here, we present the first demonstration of Doppler laser cooling of trapped atoms with broadband light pulses from an ultrafast modelocked laser. While you can only reach temperatures as low as a few K with this method, this can still be useful for the previously mentioned entanglement schemes where you only need the ions to be crystallized, rather than cooled to the ground state of motion.





Far Left: A large crystal of ions partially illuminated by our mode-locked laser. Here, *all* ions within the beam waist are visible due to the large bandwidth; as compared to a narrow-band cw laser where only specific isotopes are visible.
Right Upper: Measured ion temperature plotted against pulsed laser detuning. The solid line represents the theoretically predicted temperature (*not a fit*), while the dotted line corresponds to this theory with additional rf heating.
Right Lower: Photon scatter rate from a single, cold ion as a function of pulsed laser detuning. The solid line is a fit using a sech^2 spectrum.